Effect of Sample Bias on Paleodemographic Fertility Estimates

RICHARD R. PAINE* AND HENRY C. HARPENDING
Department of Anthropology, University of Utah,
Salt Lake City, Utah 84113

KEY WORDS skeletal series; reference sample bias; infant underenumeration

ABSTRACT Paleodemographers must work to understand how representative any archaeologically recovered skeletal series is and the potential effects of series bias on their demographic reconstructions. We examine two forms of bias: 1) infant underenumeration caused by differential preservation or incomplete archaeological recovery and 2) the underenumeration of individuals over age 45 related to methodological bias. We generated 60 simulated skeletal series of 250 individuals each based on the Brass ([1971] Biological Aspects of Demography (London: Taylor and Francis), pp. 69–110) logit models. In the first test, age bias was introduced deterministically for all individuals with age at death over 40 years using the Lovejoy et al. ([1985] Am. J. Phys. Anthropol. *68:*1–14) bias estimates. In the second test, 50% of all individuals under 5 years old were removed from each simulated distribution. The simulated series were analyzed using the model life table fitting procedure developed by the authors (Milner et al. [1989] Am. J. Phys. Anthropol. *80:*49–58; Paine [1989] Am. J. Phys. Anthropol. *79:*51–62). Forms of adult age estimation bias described by Lovejoy and coworkers inflate estimates by 10–20% of the true crude birth rate (CBR) (the number of births per year per 1,000 population). Overestimation of fertility and birth rates increases both absolutely and as a percentage of the true rate as population growth increases. This bias is very consistent. Because Lovejoy and colleagues have estimated the methodological bias itself, its effects can be estimated. Infant underenumeration is a more serious obstacle. It is not presently possible to estimate infant underenumeration reliably without prior knowledge of fertility rates. This reduces fertility reconstructions based on infant-biased samples to minimum fertility estimates. Am J Phys Anthropol 105:231–240, 1998.

Exactly what skeletons can tell us about prehistoric demography is a subject of continuing debate (Bocquet-Appel and Masset, 1996; Konigsberg and Frankenberg, 1994; Paine, 1997a; Wood et al., 1992). Despite these wider debates, there is fairly broad agreement that fertility is the demographic characteristic we can best reconstruct from skeletal series (Johansson and Horowitz, 1986; Konigsberg and Frankenberg, 1994; Milner et al., 1989; Paine, 1989a; Sattenspiel and Harpending, 1983). However, estimates of prehistoric fertility, as all paleodemographic reconstructions, are dependent on the representativeness of the skeletal series. Identifying potential sources of bias in archaeological skeletal series and their potential effects on paleodemographic reconstructions should be an integral step in any paleodemographic study (Buikstra and Konigsberg, 1985; Konigsberg and Frankenberg, 1992; Ubelaker, 1984).

*Correspondence to: Richard R. Paine, Department of Anthropology, 102 Stewart Building, University of Utah, Salt Lake City, UT 84113. E-mail: paine@anthro.utah.edu

Received 9 July 1996; accepted 12 November 1997.

This paper will examine how two specific forms of bias, infant underenumeration caused by differential preservation or incomplete archaeological recovery and misidentification of individuals over age 45 related to methodological bias, can affect paleodemographic reconstructions. Specifically, we will describe how the two forms of bias may affect estimates made using the model life table fitting procedure developed by the authors (Milner et al., 1989; Paine, 1989a,b, 1992; Paine and Harpending, 1996). In the case of skeletons over age 45, we will use the estimates of adult aging bias described by Lovejoy et al. (1985). We would emphasize that, though these are significant problems, unexpected age-at-death patterns are not always the product of archaeological processes or methodological bias. Unexpected patterns may reflect important cultural or biological phenomena. Each skeletal series must be understood individually. Assessing the degree of bias in a series is an essential step toward identifying and understanding more interesting phenomena.

FACTORS AFFECTING AGE-AT-DEATH DISTRIBUTIONS

Factors that may bias archaeological skeletal series are numerous and diverse. However, they can be generalized as falling into four basic categories: 1) culture-based biases in deposition, resulting from the study population's treatment of the dead or other cultural behaviors; 2) taphonomic processes, such as differential preservation of infant skeletons caused by natural processes acting upon the archaeological record; 3) archaeological recovery, including problems of infant recovery related to archaeological strategies or methods; and 4) bias in age estimation methods. Taphonomic processes are probably the most important factor leading to infant counts below expectation (Gordon and Buikstra, 1981; Walker et al., 1988), but age-related burial practices are another important variable (Konigsberg and Frankenberg, 1994). We suspect that bias in methods of determining the age of skeletons (Bocquet-Appel and Masset, 1982; Konigsberg et al., in press; Lovejoy et al., 1985) is a primary factor causing underrepresentation of older adults. However, older adults may also be misrepresented because of differential burial treatment (Storey and Hirth, in press; Zurn, 1970) or differential preservation (Gordon and Buikstra, 1981; Walker et al., 1988).

Cultural phenomena

Mortuary behavior. A dramatic example of a cultural practice that would bias recovery of segments of a population is the hill-grave cemetery of the Hallstatt (early Iron Age) period in central Europe (Zurn, 1970). Cemeteries were constructed around the burial hill of a community leader, locally referred to as a prince, who was almost always an adult male. Other individuals were positioned according to their relative social status and presumably their relationship to the prince. This practice leads to extreme underrecovery of both females and subadults, especially infants. Inclusion in the skeletal sample reflects social status, which is highly correlated with demographic characteristics, specifically age and sex. In this case, knowledge of the cultural pattern precludes attempts at detailed studies of many biological conditions. It also helps avoid invalid demographic reconstructions based on such series.

Other behavioral patterns. Changes in patterns of age at death may be the result of living behaviors such as warfare. Zimmerman and colleagues uncovered a unique age pattern of death at the Crow Creek massacre site (Zimmerman et al., 1981). Because the attack exposed all individuals present in the village to an extremely high risk of death, regardless of age, the age pattern better reflects the living age distribution of village inhabitants than it does a typical age pattern of death. A similar case is found at a site referred to as Norris Farms #36 in the Illinois River Valley (Milner et al., 1989). Here, chronic warfare and raiding led to greater numbers of young adult deaths than would be expected (Milner et al., 1989). To reconstruct overall fertility, Milner and colleagues apportioned individuals who died violently according to the overall adult age-at-death pattern. This resulted in a more typical model uniformitarian pattern (Milner et al. compared the series to the Coale

and Demeny [1966, 1983] West model life tables), with fertility estimates approximating contemporary horticultural groups such as the Yanomamo (Milner et al., 1989). It also served as a means of describing the population-level effects of warfare and raiding at Norris Farms #36.

Archaeological processes

Individual age at death itself may be a biasing factor in archaeological recovery because it may affect individual preservation. Infant and juvenile bones are smaller and lighter than adult bones. Their small size and incomplete calcification diminishes the likelihood that infant and juvenile bones will survive chemical or physical degradation processes long enough to be recovered archaeologically (Gordon and Buikstra, 1981). In many cases, the probability of juvenile underepresentation appears to decrease with age (Buikstra et al., 1986; Gordon and Buikstra, 1981; Walker et al., 1988). Walker and coworkers (1988) attempted to quantify the extent of preservation bias by comparing burial records and recovered skeletons from the mission cemetery at Mission La Purisima, California. People who were younger than 18 years of age made up 32% of the burial record, but only 6% of the skeletal collection. In addition, the bones of recovered individuals at Mission La Purisima and at a nearby prehistoric cemetery showed bias in completeness and preservation, with young adults better preserved than infants, children, or the elderly (Walker et al., 1988). Walker and colleagues suggest that this may be an extreme example of a common pattern, because sandy soils and seasonal soaking and drying had created particularly poor preservation conditions at the site (Walker et al., 1988).

Secondary disturbance by the culture under study may also affect archaeological recovery. In the El Cajón region of Honduras, Storey and Hirth (1997) identified mortuary patterns that combined with prehistoric reuse of structure materials to cause juvenile underenumeration. A common pattern was to bury individuals in residential platforms. Abandoned residential platforms were systematically mined to reuse as fill in later constructions, resulting in the destruction of many primary interments. When Storey and Hirth compared primary burials and secondary mortuary context, they found significant differences in subadult representation. Subadults were three times as frequent in the primary burial context as in mortuary occurrences in mounds (Storey and Hirth, 1997). Most of the difference was in subadults under age five. Storey and Hirth attribute this difference to the relative inability of young subadult skeletons to survive casual excavation and redeposition in construction fill.

TABLE 1. Bias in multifactorial age determinations, grouped by actual age in years[1]

Actual age (in years)	Bias in summary age estimates (in years)
18–29	+1.4
30–39	−0.8
40–49	−7.4
50–59	−6.8
60+	−13.6

[1] After Lovejoy et al. (1985).

Age estimation bias

The methods used to estimate age in skeletons may also introduce bias. Lovejoy et al. (1985) have attempted to quantify the age estimation bias associated with commonly employed age indicators. They demonstrated (Table 1) a pattern of increased negative age bias in individuals over age 40. Lovejoy and coworkers (1985) attribute this phenomenon to two factors. The first is substantial bias in each of three common age indicators—the pubic symphysis, auricular surface, and cranial suture closure—each of which tended to underage adult individuals, especially those over age 40. This bias is caused primarily by reference sample influences (see below). The second source of bias, according to Lovejoy et al. (1985) is an artifact of averaging age indicators, especially when one age class is open-ended. This form of bias is inherent to the aging techniques we employ (Bocquet-Appel and Masset, 1982; Konigsberg and Frankenberg, 1992, 1997); it is not a question of the skills of individual investigators. An excellent archaeological example of this pattern comes from the skeletal series from the Sunwatch Village site in Ohio (Fig. 1) which

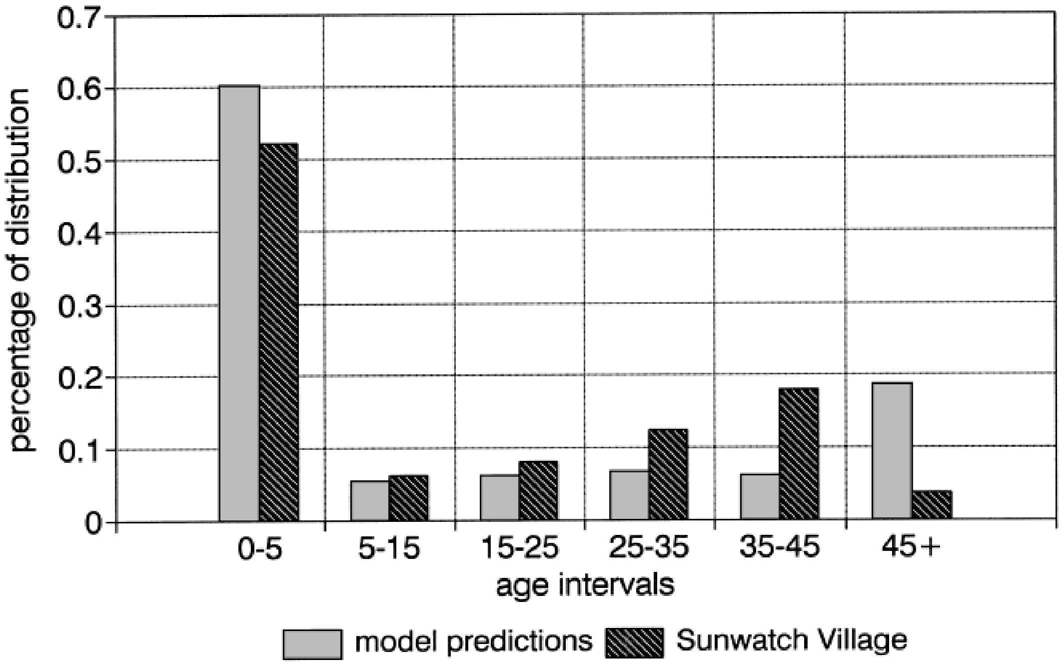

Fig. 1. Age-at-death distribution of skeletal series from the Sunwatch Village, Ohio, compared to the best-fitting Coale and Demeny (1966) west model life table death distribution. Note greater percentage of adults between 35 and 45 years and lower percentage of individuals 45+ years of age in the Sunwatch sample. (Courtesy of Paul R. Sciulli, Ohio State University.)

shows good infant preservation but significant variation from expected patterns of adult death. This variation closely resembles the patterns of late adult directional bias described by Lovejoy and coworkers (1985).

Patterns of bias are introduced by statistical methods used to relate biological indicators to chronological age. Several authors, including Bocquet-Appel and Masset (1982, 1985, 1996) and Konigsberg et al. (1992, 1997), have shown that bias in skeletal age estimates may be attributed to inverse regression methods used to establish skeletal age markers. Bocquet-Appel and Masset (1985:108) termed this problem "reference population influence." Common age estimation treats chronological age as being conditional on a biological indicator in a reference sample. This in turn makes the distribution of ages in the archaeological sample at least partially dependent on the reference sample age distribution (Bocquet-Appel and Masset, 1982; Konigsberg and Frankenberg, 1992, 1997). Bocquet-Appel and Masset consider reference sample bias the "most serious source of error affecting methods of age estimation" (Bocquet-Appel and Masset, 1982:322–323, 1985:108).

METHODS

Simulated skeletal series

To assess the degree that bias in archaeologically recovered skeletal series might affect fertility estimates, we needed series where we knew 1) the actual demographic rates that created them and 2) the pattern and extent of bias. Because such series are not readily available in the real world, we relied on computer-simulated skeletal samples (after Paine and Harpending, 1996).

Simulated skeletal samples were generated using the Brass (1971) relational system of model life tables. The Brass logit system for generating model life tables is based on a generic human survival function given by Brass as values of l_x at ages 1, 5, 10, 15, . . . , 100 (Newell, 1988). The expectation of life at birth for Brass's standard survival function is about 50 years (Newell, 1988).

This function can be transformed by a logit transformation into any of a family of curves by varying either of two parameters. The first parameter measures overall mortality. The second measures the ratio of mortality early in the lifespan to mortality late in the life span. Brass (1971) shows that this set of curves provides a good description of the mortality experience of human populations over a wide range of levels of overall mortality. We use the Brass method for computational convenience and to maintain independence from the model West-based procedure being tested, but it is our experience that using Brass (1971) models, the Coale and Demeny (1966, 1983) models, or any other set of model tables makes little or no difference to our results.

Since we wanted to simulate the proportions of deaths at the very ages that a population would leave, we needed some further manipulation to generate our model death distributions. We interpolated through the survival function values given by Brass (1971) with a spline so we would have year-by-year values. The successive differences of these values give the risk of death by year for a newborn, and the risk of a person age $\times$ dying before age $\times + 1$ is given by

$$d_x = \frac{1_x - 1_{x+1}}{1_x}.$$

It is well known that the age distribution of the living in a stable population is given by

$$p_x = e^{-rx} 1_x.$$

So the expected number of deaths is proportional to $p_x d_x$.

$$p_x d_x = e^{-rx} (1_x - 1_{x+1}).$$

Given the distribution of expected ages at death, we generated simulated skeletal samples by drawing uniformly distributed random numbers and binning them according to the cumulative distribution of skeletal age. For example, if the probability of dying before age 40 is 0.5 and the probability of dying before age 50 is 0.6, then any random number drawn that is between 0.5 and 0.6 contributes a death to the age category 40–49. We generated 180 simulated skeletal samples of various sizes (N = 50, 100, 250) from three hypothetical populations with known demographic rates. These sample sizes are fairly typical of most archaeological skeletal collections. The base populations were either expanding ($r = .01$; crude birth rate (CBR) = 31), stationary ($r = 0$; CBR = 23), or rapidly declining ($r = -.01$; CBR = 16), yet all had the same life expectancy. Growth differences resulted from different fertility rates.

Methodological bias: Age-at-death estimation. In the first test, the 60 simulated skeletal distributions were altered to examine the effect of methodological bias in age estimates on fertility estimates. Possible effects of bias in age-at-death estimates were studied using the Lovejoy et al. (1985) analysis of bias inherent to common age estimation methods (Table 1). Bias figures were based on the Lovejoy et al. multifactorial age determination "summary" age bias estimates (Lovejoy et al., 1985:7). The results of their test 1 were used. The test 2 estimates involved a recalibration of methods based upon observed—test 1—error between multifactorial age estimates and known ages from a sample of the Hamon-Todd skeletal collection. This is a situation unavailable in studies of archaeological skeletal series.

Age bias was introduced deterministically for all individuals with age at death over 40 years. Bias was considered insignificant in individuals below 40 years age at death. In the simulated skeletal samples, age at death is distributed in single year intervals. The Lovejoy et al. (1985) bias estimate was added to each individual death; for example, an individual age 50 became 43.2 years old at death (Lovejoy et al. estimated bias for individuals 50–59 equals −6.8 years). Counts for the age categories used in the model life table fitting procedure were adjusted accordingly (for examples, see Fig. 2a–c).

Archaeological bias: Infant underenumeration. The 60 simulated skeletal distributions of 250 individuals each were also intentionally biased to examine the effect of infant underenumeration on fertility estimates (Fig. 2a–c). In each case, 50% of all children 4 years of age and younger were removed from the simulated distribution. Because infants were subtracted from the

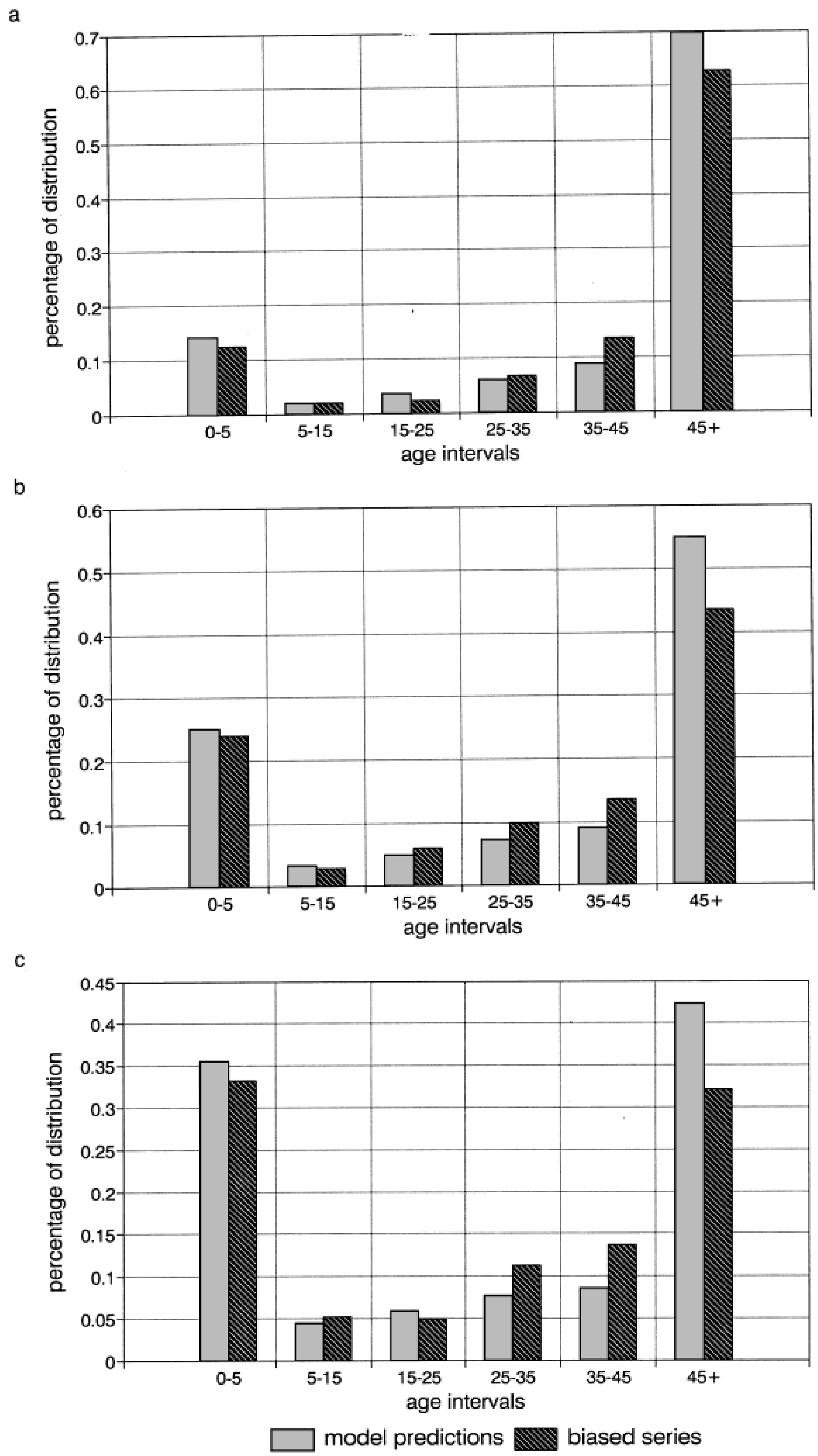
a
percentage of distribution
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0-5
5-15
15-25
25-35
35-45
45+
age intervals
b
percentage of distribution
0.6
0.5
0.4
0.3
0.2
0.1
0
0-5
5-15
15-25
25-35
35-45
45+
age intervals
c
percentage of distribution
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0-5
5-15
15-25
25-35
35-45
45+
age intervals
model predictions
biased series

Fig 2.

TABLE 2. Standard deviations (s) of CBR estimates based on both unbiased and biased simulated skeletal series

Standard deviation (s) of unbiased estimate[1] from true CBR			s given 50% infant underenumeration (from unbiased estimate)			s given Lovejoy et al. (1985) adult age bias estimates (test 1) (from unbiased estimates)		
True CBR	s	s/CBR	True CBR	s	s/CBR	True CBR	s	s/CBR
16	2.524	0.1577	16	3.613	0.2258	16	2.026	0.1266
23	1.762	0.0766	23	5.835	0.2537	23	3.086	0.1342
31	2.513	0.0811	31	6.898	0.2225	31	6.027	0.1944

[1] Each test includes 60 simulated series. The number of individuals in each unbiased series and in each series biased according to the Lovejoy et al. (1985) bias estimates is 250. The number of individuals in each of the infant underenumerated series was 250 before the removal of 50% of individuals 0–4 years of age. Sample size therefore varies.

simulated series based on a percentage loss, the size of the analyzed samples is not uniform. Each series was reanalyzed using the same procedure as for the adult aging biased samples.

No causal mechanism was ascribed to account for infant underenumeration. Infant loss may be the result of cultural deposition factors (e.g., Storey and Hirth, 1997; Sullivan, 1997), natural processes (Walker et al., 1988), or bias in archaeological recovery. We would not consider biological factors which may affect the number of infant deaths (e.g., Lovejoy et al., 1977) infant loss. We would expect the degree of infant loss to vary considerably from series to series. Under ideal circumstances, all infants may be recovered, while the majority infants may be lost in especially poor preservation conditions (e.g., The Mission La Purisima cemetery [Walker et al., 1988]). We do not suggest that the 50% figure is typical.

RESULTS

The forms of age estimation bias described by Lovejoy and coworkers (Lovejoy et al., 1985) cause overestimation of fertility and birth rates. This overestimation bias increases both absolutely and as a percentage of the true value in higher fertility populations (Tables 2, 3; Fig. 3). However, assuming the accuracy of the situation described by Lovejoy et al. (1985), this bias is both consistent and predictable. Adult age estimation bias inflates estimates by 10–20% of the true CBR value. Therefore, the effects of this form of bias can be accounted for in fertility and birth rate analyses with relative confidence. Returning to the skeletal series from the Sunwatch Village, if the best-fitting west model has a crude birth rate of 56, we would estimate that the actual CBR might be in the range of 40–45 (the best-fitting model has a CBR well above our highest simulated population). As bias increases with increases in CBR, we would expect bias for this sample to be somewhat greater than 20%.

Fifty percent infant underenumeration depresses both fertility and birth rate estimates by between 20 and 25% (Fig. 3). Unlike the bias caused by adult age estimation methods, directional bias caused by infant underenumeration appears to be independent of changes in birth rates. Though there must be an easily quantifiable relationship between the degree of infant underenumeration and the degree of bias in CBR estimates, describing such a relationship is not useful unless we have an archaeological means of estimating infant loss (for an attempt to estimate such infant underrecovery, see Storey and Hirth, 1997).

Fig. 2. The effect of sample bias on simulated age-at-death distributions. **a:** Declining population; r = −.01, CBR = 16 (simulated series 3). **b:** Stationary population; r = 0, CBR = 23 (simulated series 23). **c:** Expanding population, r = .01, CBR = 31 (simulated series 49). Lightly shaded bars show unbiased distribution. Dark crosshatched bars indicate effects of pattern of adult aging bias identified by Lovejoy et al. (1985).

TABLE 3. Mean distance between biased sample CBR estimates and unbiased sample estimated expressed as a percentage of the true CBR

True CBR	Unbiased	Adult aging bias	50% infants
Overall	−4.72	13.38	−22.84
CBR = 16	−8.44	10.27	−21.85
CBR = 23	−2.83	11.45	−25.02
CBR = 31	−2.90	18.37	−21.86

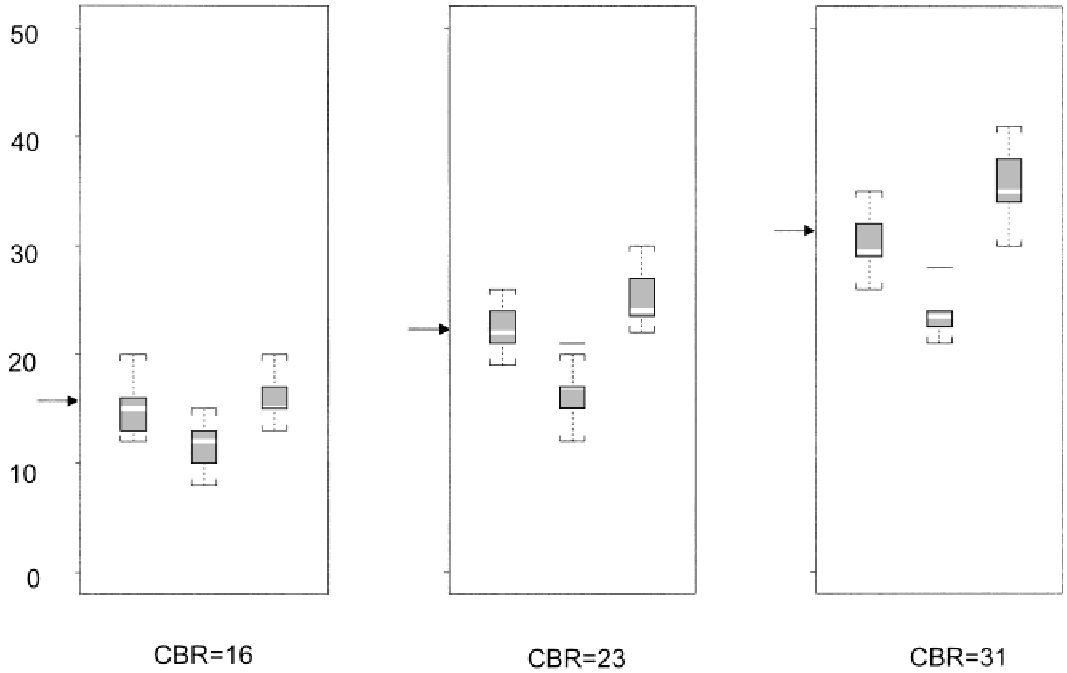

Fig. 3. Boxplots of the effect of bias on birthrate estimates. The true population CBR is marked by an arrow on each panel. The left plot in each panel represents estimates based on unbiased samples. Variation in unbiased estimates results from stochastic variation in sample distributions. The center plot in each panel shows the effect of Lovejoy et al. (1985) pattern adult aging bias on CBR reconstruction. The right plot in each panel represents the effect of 50% infant underenumeration on CBR reconstruction. Stochastic variation in number of 0–5 individuals yields varying amounts of bias by individual series. Note: the size of individual simulated samples is 250, except for samples with infant underenumeration. The size of these samples depends on the number of individuals 0–5 years in the sample before 50% were removed.

Table 3 also demonstrates the strong resemblence between the Brass (1971) relational life tables and the Coale and Demeny "West" models. The CBRs of the best-fitting West models are, on average, 4.72% lower than the true (Brass) CBR values when we analyze the unbiased series. This bias reflects small-scale differences in the shape of mortality patterns between the two life table models.

DISCUSSION

Archaeological skeletal series frequently exhibit proportions of infants and/or the elderly well below expectations based on modern populations or model life tables (Lovejoy et al., 1977; Paine, 1989b; Weiss, 1973). In some cases, deviations from expected death distributions may be due to biological factors. This has been suggested for the well-known Libben population in Ohio (Lovejoy et al., 1977). These cases are of the utmost interest, and their explanation should be an important pursuit. However, deviation from uniformitarian patterns should not be assumed to indicate biological (or cultural) phenomena. Such assertions should be based on specific testable models.

Several examples of such modeling have been attempted. Paine (1992, 1997b) modeled probable effects of migration on skeletal age distributions and showed that patterns of migration typical of present-day populations (Rogers and Castro, 1982) would not produce the pattern of young adult overrepresentation typical of many archaeological skeletal series. Keckler (1997) has modeled the effects of explicit violations of the stability assumption on age-at-death distributions. His models of biphasic mortality do produce greater percentages of young adults than stable models.

Others have attempted to counteract methodological bias in skeletal age-at-death estimates. Lovejoy and colleagues' (1985) attempts to quantify the age estimation bias inherent to several prevalent skeletal indicators formed the basis of this study of adult aging bias. Several authors (e.g., Konigsberg et al., 1997; Skythe and Boldsen, 1993) have attempted to alleviate the problem of reference sample bias (Bocquet-Appel and Masset, 1982, 1985) characteristic of skeletal age estimation methods. Skythe and Boldsen (1993) and Konigsberg and Frankenberg (1992) have both applied maximum likelihood estimation techniques to remove methodological bias from age-at-death distributions. In contrast to Bocquet-Appel and Masset (1996), we are confident that these efforts will prove effective.

Infant underenumeration is a much more serious obstacle. Both infant underenumeration and adult age bias have predictable effects on estimates. The degree of methodological (adult age) bias itself can be quantified (e.g., Lovejoy et al., 1985). Therefore, its effects can be estimated. The inability to estimate infant loss reliably without prior knowledge of fertility rates reduces fertility reconstructions based on infant-biased samples to minimum fertility estimates. How much higher actual fertility (and birth) rates may have been cannot be accurately reconstructed without accurate estimates of the infant underenumeration. Several formulae for reconstructing fertility are available that avoid the problem of infant underenumeration by limiting analysis to older age categories (e.g., Bocquet-Appel and Masset, 1982; Buikstra et al., 1986). Unfortunately, reconstruction methods that omit the infant segment of samples appear to be less sensitive to changes in fertility than methods that include all ages (Paine and Harpending, 1996). In addition, as pointed out by Konigsberg (personal communication), both Bocquet-Appel and Masset (1982) and Buikstra and Konigsberg (1985) used inverse regression (i.e., they regressed CBR on some death ratio rather than the other way around), so their estimates take an informative prior for CBR from the reference data.

The key to understanding variation in the age patterns of archaeological skeletal series is control over the archaeological data. This requires placing paleodemographic studies solidly within an integrated archaeological strategy (Paine, 1997a). We must have basic settlement-based estimates of the overall demographic patterns such as population growth (Johansson and Horowitz, 1986) and density (Storey and Hirth, 1997). We must have basic control over the cultural setting and a knowledge of possible cultural or biological conditions, such as warfare or epidemic disease, that may affect age-at-death patterns (these should be explicitly described [see Paine, 1997b]). Control of the archaeological context is the best means to control paleodemographic data. If it is to be successful, paleodemographic study cannot and must not be an isolated endeavor.

ACKNOWLEDGMENTS

Lyle W. Konigsberg, George R. Milner, James W. Wood, and two anonymous reviewers made valuable comments on earlier versions of this paper. Paul R. Sciulli generously allowed us to use the Sunwatch skeletal series as a case example. Portions of the paper were completed while Paine was a Charles P. Taft Postdoctoral Fellow at the University of Cincinnati. We would like to thank the Taft Trustees and the UC Department of Anthropology, Alan P. Sullivan, chair, for their support and hospitality.

LITERATURE CITED

Bocquet-Appel JP, and Masset C (1982) Farewell to paleodemography. J. Hum. Evol. *11:*321–333.

Bocquet-Appel JP, and Masset C (1985) Paleodemography: Resurrection or ghost? J. Hum. Evol. *14:*107–111.

Bocquet-Appel JP, and Masset C (1996) Paleodemography: Expectancy and false hope. Am. J. Phys. Anthropol. *99:*571–583.

Brass W (1971) On the scale of mortality. In W Brass (ed.): Biological Aspects of Demography. London: Taylor and Francis, pp. 69–110.

Buikstra JE, and Konigsberg LW (1985) Paleodemography: Critiques and controversies. Am. Anthropologist *87:*316–333.

Buikstra JE, Konigsberg LW, and Bullington J (1986) Fertility and the development of agriculture in the prehistoric Midwest. Am. Antiquity *51:*528–546.

Coale AJ, and Demeny P (1966) Regional Model Lifetables and Stable Populations. Princeton, NJ: Princeton University Press.

Coale AJ, and Demeny P (1983) Regional Model Lifetables and Stable Populations. New York: Academic Press.

Gordon CG, and Buikstra JE (1981) Soil pH, bone preservation, and sampling bias at mortuary sites. Am. Antiquity *46:*566–571.

Johansson SR, and Horowitz S (1986) Estimating mortality in skeletal populations: Influence of the growth rate on the interpretation of levels and trends during the transition to agriculture. Am. J. Phys. Anthropol. *71:*233–250.

Keckler CNW (1997) Where did all the humans go? Simulating forager age-at-death distributions with a biphasic model of mortality. In RR Paine (ed.). Integrating Archaeological Demography: Multidisciplinary Approaches to Prehistoric Population. Occasional Papers 24. Carbondale: Center for Archaeological Investigations, pp. 205–228.

Konigsberg LW, and Frankenberg SR (1992) Estimation of age structure in anthropological demography. Am. J. Phys. Anthropol. *89:*235–256.

Konigsberg LW, and Frankenberg SR (1994) Paleodemography: Not quite dead. Evol. Anthropol. *3*:92–105.

Konigsberg LW, Frankenberg SR, and Walker RB (1997) Regress what on what? Paleodemographic age estimation as a calibration problem. In RR Paine (ed.): Integrating Archaeological Demography: Multidisciplinary Approaches to Prehistoric Population. Occasional Papers 24. Carbondale: Center for Archaeological Investigations, pp. 64–88.

Lovejoy CO, Meindl RS, Pryzbeck TR, Barton TS, Heiple KG, and Kotting D (1977) Paleodemography of the Libben Site, Ottawa County, Ohio. Science *198:*291–293.

Lovejoy CO, Meindl RS, Mensforth RP, and Barton TS (1985) Multifactorial determination of skeletal age at death: A method and blind tests of its accuracy. Am. J. Phys. Anthropol. *68:*1–14.

Milner GR, Humpf DA, and Harpending HC (1989) Pattern matching of age-at-death distributions in paleodemographic analysis. Am. J. Phys. Anthropol. *80:*49–58.

Newell C (1988) Methods and Models in Demography. New York: Guilford Press.

Paine RR (1989a) Model life table fitting by maximum likelihood estimation: A procedure to reconstruct paleodemographic characteristics from skeletal age distributions. Am. J. Phys. Anthropol. *79:*51–62.

Paine RR (1989b) Model life tables as a measure of bias in the grasshopper pueblo skeletal series. Am. Antiquity *54:*820–824.

Paine RR (1992) Population Dynamics at Copán, Honduras, AD 450–1250: A Study in Archaeological Demography. PhD dissertation, Pennsylvania State University. Ann Arbor: University Microfilms.

Paine RR (1997a) The need for a multidisciplinary approach to prehistoric demography. In RR Paine (ed.): Integrating Archaeological Demography: Multidisciplinary Approaches to Prehistoric Population. Occasional Papers 24. Carbondale: Center for Archaeological Investigations, pp. 1–20.

Paine RR (1997b) The use of uniformitarian models in osteological paleodemography. In RR Paine (ed.): Integrating Archaeological Demography: Multidisciplinary Approaches to Prehistoric Population. Occasional Papers 24. Carbondale: Center for Archaeological Investigations, pp. 191–204.

Paine RR, and Harpending HC (1996) The reliability of paleodemographic fertility estimators. Am. J. Phys. Anthropol. *101:*151–160.

Rogers A, and Castro LJ (1982) Model schedules in multistate demographic analysis: The case of migration. In KC Land and A Rogers (eds.): Multidimensional Mathmatical Demography. New York: Academic Press, pp. 113–154.

Sattenspiel L, and Harpending HC (1983) Stable Population and Skeletal Age. Am. Antiquity *48:*489–498.

Skythe A, and Boldsen JL (1993) A method for construction of standards for determination of skeletal age at death. Am. J. Phys. Anthropol. Suppl. *16:*182.

Storey R, and Hirth K (1997) The El Cajón, Honduras, skeletal population: Archaeological and paleodemographic approaches to understanding juvenile underrepresentation and low population fertility. In RR Paine (ed.): Integrating Archaeological Demography: Multidisciplinary Approaches to Prehistoric Population. Occasional Papers 24. Carbondale: Center for Archaeological Investigations, pp. 131–149.

Sullivan NC (1997) Contact period Huron demography. In RR Paine (ed.): Integrating Archaeological Demography: Multidisciplinary Approaches to Prehistoric Population. Occasional Papers 24. Carbondale: Center for Archaeological Investigations, pp. 327–343.

Ubelaker DH (1984) Human Skeletal Remains: Excavation, Analysis, Interpretation, revised ed. Washington, DC: Taraxacum.

Walker PL, Johnson JR, and Lambert PM (1988) Age and sex biases in the preservation of human skeletal remains. Am. J. Phys. Anthropol. *76:*183–188.

Weiss KM (1973) Demographic Models for Archaeology. SAA Memoir 27. Washington, DC: Society for American Archaeology.

Wood JW, Milner GR, Harpending HC, and Weiss KM (1992) The osteological paradox. Current Anthrop. *33:*343–370.

Zimmerman J, Emerson T, Willey P, Swegle M, Gregg J, Gregg P, White E, Smith C, Haberman T, and Bumsted M (1981) The Crow Creek Site (39BF11) Massacre: A Preliminary Report. Omaha: Omaha District, US Army Corps of Engineers.

Zurn H (1970) Hallstattforschungen in Nordwurttemberg. Die Grabhugel von Asberg (Kr. Ludwigsburg), Hirschlanden (Kr. Leonberg) und Muhlacker (Kr. Vaihingen). Stuttgart: Verlag Muller und Graff.